

Final Report Submitted to the
Air Force Office of Scientific Research
for research on

Manipulating Local Electronic Properties of Carbon Nanotubes
Agreement # FA9550-08-1-0427

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Objectives:

Carbon nanotubes have many emerging technological uses, from strengthening lightweight composite materials to reducing voltage requirements in field-emission displays. Companies such as IBM and Intel have substantial research efforts aimed at the more complex task of building transistors and computer processors from nanotubes. Research under this proposal addresses one of the important requirements for achieving that vision: understanding and modifying electron flow in one-dimensional systems (carbon nanotubes) by local gating, to create transistors. By agreement with the program officer, this effort was broadened to explore electron flow in other 1D conductors (semiconductor nanowires) and electronic states in other carbon nanomaterials (graphene).

Status of effort:

As of the end of funding, July 31, 2011, funding had been going for three years on this project.

Accomplishments:

1. We discovered that it is possible to drive spin currents through semiconductor nanowires using a combination of spin-orbit coupling and external magnetic fields. This has already shaped thinking worldwide about the relationship between such nanowire systems and topological insulators, a novel class of materials which shows unusual spin transport at edges or surfaces.

2. We developed one of the world's most sensitive capacitance measurement systems (in collaboration with Philip Wong, Stanford Electrical Engineering). This can be used to measure density of states in gated nanodevices (notably carbon nanotubes) and thus to extract meaningful mobility for such devices, study defect states, and other things conventionally done by C-V profiling on larger devices. It can be used to measure capacitances at attoFarad resolution, at room temperature or down to 4 Kelvin.

3. We experimentally and theoretically clarified the physics of electrical contact to graphene, and electron flow across graphene p-n junctions, basic building blocks for any graphene electronics.

Personnel supported or associated with work:

Principal Investigator:

David Goldhaber-Gordon, Assistant Professor of Physics

Graduate students (external fellowships supplemented):

Charis Quay, Ph.D. student in Physics: working on nanotube transistors and nanotube variants: "peapods". Graduated Dec. 2007.

Joseph Sulpizio, Ph.D. student in Physics: working on semiconductor nanowires and

precision capacitance measurements on graphene. Graduated Dec. 2010.

Undergraduate (Stanford supplemented):

Patrick Gallagher, Graduated June 2010. Worked on graphene nanoribbons and the role of disorder and interactions in these systems

Publications or notable interactions:

- J. A. Sulpizio, C. Quay, D. Goldhaber-Gordon, and R. DePicciotto, “Spin and interaction in 1D hole wires”, *In Preparation* (2011).
- A. Hazeghi, J. A. Sulpizio, G. Diankov, D. Goldhaber-Gordon, and H. S. Philip Wong. “An integrated capacitance bridge for high-resolution, wide temperature range quantum capacitance measurements”, *Review of Scientific Instruments* **82**, 053904 (2011).
- C. H. L. Quay, T. L. Hughes, J. A. Sulpizio, L. N. Pfeiffer, K. W. Baldwin, K. W. West, D. Goldhaber-Gordon and R. de Picciotto. “Observation of a one-dimensional spin–orbit gap in a quantum wire”, *Nature Physics* **6**, pp 336-339 (2010).

The following acknowledged the grant which this one was a renewal of, rather than this grant itself, **but were not published until after the previous grant’s final report was submitted, and did benefit** from the present grant:

- J. Cayssol, B. Huard, D. Goldhaber-Gordon. “Contact resistance and shot noise in graphene transistors”, *Phys. Rev. B* **79**, 075428 (2009).
- N. Stander, B. Huard, D. Goldhaber-Gordon. “Evidence for Klein Tunneling in Graphene p-n Junctions”, *Phys. Rev. Lett* **102**, 026807 (2009). Supplementary info.
- K. Todd, H.T. Chou, S. Amasha, D. Goldhaber-Gordon. “Quantum Dot Behavior in Graphene Nanoconstrictions”, *Nano Lett.* **9** 416-421 (2009). Supplementary info.
- B. Huard, N. Stander, J.A. Sulpizio, D. Goldhaber-Gordon. “Evidence of the role of contacts on the observed electron-hole asymmetry in graphene”, *Phys. Rev. B* **78**, 121402 (2008). Supplementary info.

New discoveries since latest progress report:

Development of an ultra-precise capacitance measurement system for nanodevices.

Honors/Awards:

2002 AFOSR Presidential Early Career Award in Science and Engineering (PECASE) (*actually awarded 2004*). Awarded to two early-career scientists or engineers per year.

2004 David and Lucille Packard Fellow. 16 awarded nationwide to early-career faculty across all fields of science and engineering.

2003 Alfred P. Sloan Foundation Fellowship

2004 Research Corporation Research Innovation Award

2004 Named Co-Director (with Kam Moler) of NSF-Stanford-IBM Nanoscale Science and Engineering Center: “Center for Probing the Nanoscale”

2006 National Academy of Sciences Award for Initiatives in Research

2007 Hellman Faculty Scholar

2010 Undergraduate, Patrick Gallagher, selected as finalist for Apker Award, American Physical Society’s top recognition for undergraduate physics research.